Possible Interpretation of Isotropic Gamma-Ray Observations

By comparing the theoretical calculations of isotropic γ-ray spectra from intergalactic secondary particle production (ch. 10), matter-antimatter annihilation (ch. 11), bremsstrahlung, and Compton interactions (ch. 12), we find that extragalactic bremsstrahlung and Compton interactions may be possible alternative explanations of the observed isotropic X-ray spectrum below 1 MeV. Both processes produce power-law X-ray spectra with exponents in the range from 2.4 to 2.6 from interactions involving cosmic-ray electrons having spectra similar to that of galactic electrons. However, as we showed in chapter 12, the bremsstrahlung X-rays are produced by electrons in the energy range where they are unattenuated by Compton interactions, whereas the Compton-produced X-rays result from interactions of higher energy electrons with a steeper energy spectrum, which have been attenuated by Compton interactions. Thus, as we showed in chapter 12, we can get cosmological enhancement of the bremsstrahlung X-ray spectrum at high redshifts, but such is not the case with Compton-produced X-rays.

The recent observations of Vette et al. (1969, 1970) have now provided measurements of background γ-rays with energies up to 6 MeV. (See appendix.) These data, providing the first measurements in this energy range, have already yielded valuable information. Their preliminary results are shown in figure 14–1. These measurements are consistent with the well-known power-law X-ray spectrum below 1 MeV. However, they indicate a marked departure from the power law above 1 MeV. For example, the 6-MeV point is an order of magnitude higher than what would be expected on the basis of a power-law extrapolation of the X-ray data. Also included in the figure are an upper limit set by a balloon flight of the University of Rochester group and updated by a recent recalibration and an upper limit at 10 MeV set by a balloon flight of the Naval Research Laboratory Nucleonics Division (Share, 1970). The OSO–3 point shown in the figure is based on the recent recalibration of Clark et al. (1970). The solid $p-p$ line for $z_{max}=100$ is the same as that

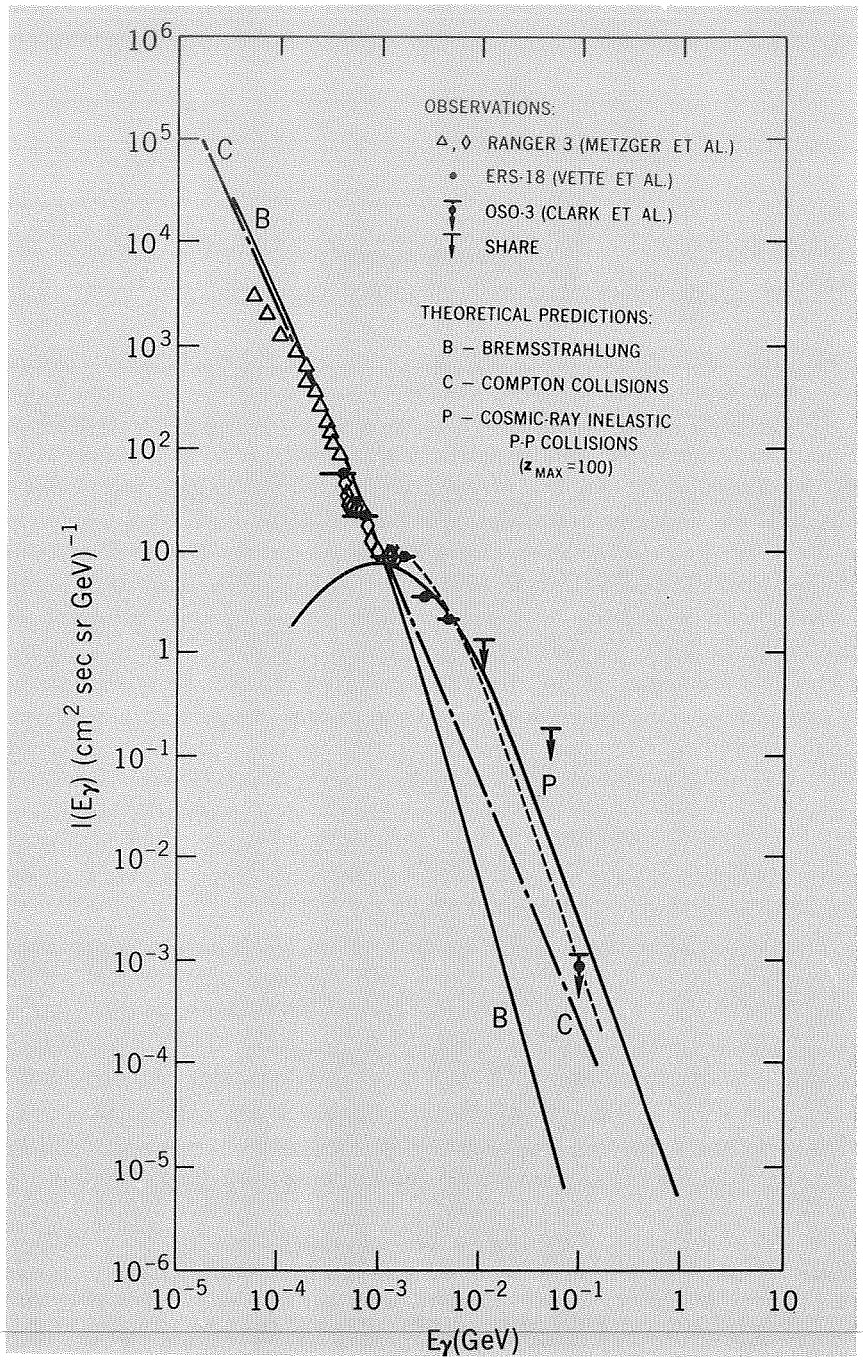

FIGURE 14–1.—Extragalactic high-energy photon spectra.

calculated in chapter 10 (Stecker, 1969c) for collisions involving cosmic rays with a power-law spectrum of exponent -2.5. The dashed line indicates the γ-ray spectrum generated by cosmic rays with a power-law spectrum of exponent -2.7. The data above 1 MeV, with the data of Clark et al. being interpreted as a real flux, fit the shape of the theoretical γ-ray spectrum from cosmic-ray p–p interactions integrated to a maximum redshift of ~ 100 for a burst or evolving source model where cosmic-ray production was higher in the past. They do not seem consistent with other theoretical spectra for energies above 1 MeV. Vette et al. (1970) have interpreted their results to indicate a new component of the cosmic γ-ray spectrum above 1 MeV which they find to be consistent with the theoretical interpretation presented here. In addition, Clark et al. (1969) have reported qualitative results indicating that the isotropic component of cosmic γ-radiation above 100 MeV has a softer spectrum than the galactic component. This result is also in agreement with the theoretical predictions presented previously.

These suggestive results make it even more imperative to obtain other γ-ray observations in the 1- to 100-MeV region in order to confirm the present data and to extend the range of the measurements. However, on the basis of these first results, we can present the following interpretation.

Comparison of the predicted spectra with the γ-ray observations indicates that extragalactic γ-radiation may be due to the decay of neutral pions produced in inelastic collisions of extragalactic cosmic-ray protons and gas. The peak in the resultant γ-ray spectrum, which normally occurs at ~ 70 MeV, is redshifted down to $\sim$ 1-MeV energy. This effect is due to the increased collision rate at larger redshifts, when our expanding universe was in a more compact state, as well as to increased cosmic-ray production at large redshifts. A cosmic-ray production rate which is constant over all redshifts will not account for the new observations. The assumption of various time-dependence models for cosmic-ray production leads to differing requirements for the present metagalactic cosmic-ray flux needed to produce the observed γ-rays. (See fig. 12–3.) The maximum redshift needed to fit the observations is ~ 100, which corresponds to an epoch when the age of the universe was 10^7 to 10^8 years and the temperature of the universal radiation field was ~ 270 K. This may correspond to the epoch when objects of galactic mass were beginning to form from the metagalactic medium (Weymann, 1967). There is mounting evidence that radio sources were more active (or prevalent) at earlier epochs (Longair, 1966; Rowan-Robinson, 1968; Schmidt, 1968) and it is plausible to speculate that in these sources, where electrons are accelerated to cosmic-ray energies, protons may also

be accelerated to these energies.[1] Whereas electrons have short lifetimes at high redshifts due to Compton interactions with the universal radiation field, possibly restricting their radio-emission stage to redshifts of ~ 10 or less, the protons do not undergo significant depletion from Compton interactions. Thus, the sources producing γ-rays at redshifts of ~ 100 will not be visible as radio sources. They may also be unobservable in the optical (Gunn and Peterson, 1965) and X-ray regions (Rees, 1969, and Arons and McCray, 1969), since a dense intergalactic medium becomes opaque to X-rays at redshifts < 10. Thus our best chance of studying these sources comes from γ-ray observations; and their study should be of prime importance to the young field of γ-ray astronomy.

I will henceforth refer to these primordial cosmic-ray sources as "protars." It seems reasonable to speculate that protars may be early stages in the evolution of quasars and galaxies; i.e., of objects of high mass that are in the initial stages of condensing out of the metagalactic medium. The subsequent release of gravitational energy coupled with the generation of strong magnetic fields during the contraction could then provide energy for the acceleration of cosmic rays.

Although most theoretical arguments favor a present intergalactic gas density of 10^{-7} to 10^{-5} cm^{-3}, studies of the spectra of quasars having redshifts of ~ 2 have indicated a neutral hydrogen density $\lesssim 10^{-11}$ cm^{-3} (Burbidge and Burbidge, 1967). This fact argues for a strongly ionized intergalactic medium. In addition, soft X-ray observations by Henry et al. (1968) have produced evidence of a hot intergalactic plasma with a density of 10^{-6} to 10^{-5} cm^{-3}. Recent comparisons of radio observations with theoretical models of free-free emission spectra from ionized intergalactic gas (Payne, 1969) have indicated that the intergalactic medium could have become ionized at some redshift $\lesssim 100$. Cosmic rays from protars would provide a natural source for heating the intergalactic medium at this epoch. It can be shown (Weymann, 1967) that once the ionization occurs, the medium would then remain ionized due to subsequent cosmic-ray heating up to the present epoch. Rees (1969b) has recently argued for an intergalactic gas remaining neutral at redshifts between ~ 2 and ~ 1000.

Cosmic rays from protars that have energies of ~ 300 MeV (the threshold for neutral pion production) at a redshift of ~ 100 would have their energy reduced to ~ 100 keV at a redshift of ~ 2 and would be about 50 times more effective in heating the intergalactic gas. Therefore, cosmic rays from protars existing out to redshifts of ~ 100 could cause a delayed ionization of the intergalactic medium effective at much lower redshifts.

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[1] Other possible implications have been suggested by the author (Stecker, 1971).

It should be pointed out that the redshifts of ~ 100 proposed here for the protars may indicate that they are near the limit of observability for γ-ray observations. Rees (1969a) and Arons and McCray (1969) have independently considered the absorption of γ-rays by intergalactic gas due to Compton interactions and pair production. In an Einstein-de Sitter universe with a gas density of 10^{-5} cm^{-3}, the γ-ray absorption coefficient varies as the 3/2 power of redshift. For a high-density universe and a redshift of $z=100$, we find from equation (13–17) that the optical depth is ~ 1.2 for γ-rays with present energies between 1 and 100 MeV.

Thus, for a high-density universe, the γ-rays reaching us may be partially depleted by absorption effects. Of course, for models with $n_0 < 10^{-5}$ cm^{-3}, absorption effects are negligible at $z=100$.

It has been shown in chapter 13 that the γ-ray opacity due to interactions with the universal blackbody radiation for $z \lesssim 100$ is negligible for $E \leqslant E_c = 7.1$ GeV. However, above this energy absorption effects become important and steepen the resultant γ-ray spectrum. The spectrum above 7.1 GeV, instead of being an integral over the range $0 \leqslant z \leqslant 100$, becomes an integral over the range $0 \leqslant z \leqslant z_{\text{crit}}$, with z_{crit} given by equation (13–11).

Thus, for $z_{\max} \gg 1$, assuming that $z_{\text{crit}} = 260\, E_\gamma^{-1/2}$, considering a burst model for cosmic-ray protons (see ch. 10), and taking $G(E_\gamma) \sim E_\gamma^{-3}$ above 10 GeV, we find from equation (9–22)

$$I(E_\gamma) \sim E_\gamma^{-3} \int_0^{260E_\gamma^{1/2}} dz(1+z)^m \sim E_\gamma^{-\left(3+\frac{m+1}{2}\right)} \qquad (14\text{–}1)$$

where $m=0$ in the case of an Einstein-de Sitter universe and $m=\frac{1}{2}$ in the case of a low-density universe. Thus, for an Einstein-de Sitter model, the exponent in the cosmological γ-ray spectrum should increase by a factor of $\Delta\Gamma_\gamma \simeq \frac{1}{2}$, and for a low-density universe the increase is $\Delta\Gamma_\gamma \simeq \frac{3}{4}$.

It should also be noted that in a high-density model at redshifts of the order of 100, cosmic-ray attenuation by nuclear collisions will also become important. (See ch. 10.) Thus, we must increase somewhat the cosmic-ray production requirements for the high-density model. However, for present densities less than 0.5×10^{-5} cm^{-3}, attenuation is negligible.

Taking absorption effects into account, and considering models where the present gas density is 10^{-7} to 10^5 cm^{-3}, we can conclude that if the protar hypothesis is correct, protars have filled intergalactic space with remnant cosmic rays having a present density of 10^{-5} to 10^{-3} the galactic value; i.e., 10^{-17} to 10^{-15} erg/cm^3.

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